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Alternatives to heavy fuel oil use in the Arctic: Economic and environmental tradeoffs

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Executive Summary

The use of heavy fuel oil (HFO)—the leftover residues from the crude oil refining process—as a marine fuel poses serious environmental and economic risks, especially in ecologically sensitive areas like the Arctic. The International Maritime Organization (IMO) has prohibited the use and carriage of HFO in the Antarctic. However, the international community has not yet implemented similar regulations for the Arctic. As Arctic sea ice melts, economically viable trans-Arctic shipping routes will become increasingly available for longer periods of the year. As ship traffic grows in the Arctic, the use and carriage of HFO will also grow, raising the risks of an HFO spill and increasing emissions of climate-warming black carbon (BC) in a region warming at more than twice the rate of the rest of the world.

This study compares the economic and environmental tradeoffs of switching from HFO to two alternative fuels, distillate fuel and liquefied natural gas (LNG), in the IMO Arctic, as defined in the IMO Polar Code. Fuel costs, fuel spill cleanup costs, and the economic and environmental costs and benefits of switching from HFO and <0.5% sulfur (S) residual fuel to alternative fuels are estimated for ships operating in the IMO Arctic for the year 2015, with projections to 2020 and 2025.

In 2015, switching from HFO to distillate would have increased fuel costs for an individual ship in the Arctic fleet by 55%. Switching all of the ships in the fleet that operate on HFO to distillate in 2015 would have increased fleetwide fuel costs by only 30%, however, because more than half of the ships in the IMO Arctic already operate on distillate fuel. In 2020 or 2025, switching from HFO to distillate would increase the fuel costs for an individual ship in the Arctic fleet by 32%. However, in 2020, the cost of switching all of the ships that operate on HFO to distillate is expected to be substantially lower, as IMO's implementation of a 0.5% global marine fuel S cap in 2020 is expected to greatly decrease the amount of HFO used by ships in the IMO Arctic. Indeed, in 2020 and 2025, HFO is expected to represent only 7% of the fuel used by ships in the IMO Arctic (down from 58% in 2015). The ships that continue to operate on HFO in 2020 and beyond will be required to install and operate an exhaust gas cleaning system (i.e., a scrubber). The study concludes that switching the Arctic ships that remain operating on HFO to distillate fuel would cost the Arctic fleet [in 2015 U.S. dollars (USD)] roughly \$4.3 million in 2020 or \$5.2 million in 2025—an increase in fleetwide fuel costs of less than 2%.

With the implementation of the 0.5% fuel S cap in 2020, most ships that currently operate on HFO are expected to use desulfurized residual fuel or residual fuel blends that comply with the standard (referred to here as <0.5% S residual fuel) instead of switching to more expensive distillate fuel or installing scrubbers. This study projects that switching all of the ships in the IMO Arctic fleet that use <0.5% S residual fuel to distillate would increase fleetwide fuel costs by \$4.5 million in 2020 or by \$5.4 million in 2025. This suggests a total cost of approximately \$9 million to \$11 million[1] (2015 USD) to switch all of the ships in the Arctic fleet that use HFO or <0.5% S residual fuel to operate on distillate in 2020 and beyond.

Although continuing to operate the Arctic fleet on HFO or residual fuel blends would offer some economic benefits relative to operating on distillate fuels, the cleanup costs (per tonne) for a residual fuel oil spill are more than 7 times those for a distillate spill. The costs of cleaning up even a relatively small spill of HFO or <0.5% S residual fuel—less than 1% of the amount of these fuels expected to be carried on ships in the Arctic in 2020 or

1 The approximate sum of switching all of the Arctic ships that operate on either HFO or <0.5% S residual fuel to distillate fuel in 2020 or 2025.

2025—would outweigh the annual cost savings of continuing to operate on these fuels. This does not account for other ecological and societal benefits of switching from HFO or residual fuel blends to distillate fuels.

The price of LNG is expected to be less than that of HFO and <0.5% S residual fuel in 2020 and 2025; however, most ships in the Arctic fleet would need to be converted to operate on LNG, which is a potentially expensive undertaking in the short term. However, it is not out of the question for ships to convert to operate on LNG in the medium term if the price of LNG remains low and ship owners accept the payback period.

This report concludes by considering a number of potential policy alternatives, including (i) prohibiting the use of any petroleum-based fuel oil in the Arctic and (ii) prohibiting the use and carriage of HFO, desulfurized residual fuel, or residual fuel blends. Prohibiting any petroleum-based fuel oil would provide the greatest long-term protection of the Arctic environment from the risks of spills and BC emissions, whereas prohibiting the use and carriage of HFO, desulfurized residual fuel, or residual fuel blends would offer a short-term solution that immediately reduces the risks associated with the use and carriage of HFO as a marine fuel. This would also avoid the potential costs of cleaning up a spill of those fuels—costs that have exceeded $100 million per incident in recent decades, far exceeding the expected fuel cost increases associated with prohibiting HFO or <0.5% S residual fuel.

A	B	C	D	E	F	G
60°00'.0N 056°37'.1W	58°00'.0N 042°00'.0W	64°37'.0N 035°27'.0W	67°03'.9N 026°33'.4W	(Sørkapp, Jan Mayen) 70°49'.56N; 08°59'.61W	(by the Island of Bjørnøya) 73°31'.6N; 019°01'.0E	(Cap Kanin Nos) 68°38'.29N; 043°23'.08E

Figure 1. The IMO Arctic.

1. Introduction

The use of heavy fuel oil (HFO)—the leftover residues of the crude oil refining process—as a marine fuel poses serious environmental and economic risks, more so in ecologically sensitive areas like the Arctic. The International Maritime Organization (IMO) has prohibited the use and carriage (as fuel and cargo) of HFO in the Antarctic. However, neither the international community nor Arctic states have implemented similar regulations for the Arctic region, with the exception of the waters around Svalbard that are part of the Norwegian national park system. The use of HFO in the Arctic not only increases the risk of severely damaging spills and illegal discharges in the Arctic but also results in harmful air and climate pollutants, including black carbon (BC).

Melting Arctic sea ice is expected to open economically viable transport routes for the maritime industry. As ship traffic increases in the Arctic, the use and carriage of HFO will also increase, posing a serious threat to the sensitive and unique Arctic marine environment in the event of an oil spill.

This study compares the economic and environmental tradeoffs of switching from HFO to two alternative fuels—distillate fuel and liquefied natural gas (LNG)—in the IMO Arctic, as defined in the IMO Polar Code (Figure 1). The study estimates the following for ships operating in the IMO Arctic for the year 2015, with projections to 2020 and 2025:

1. Fuel costs
2. Fuel spill cleanup costs
3. Economic and environmental costs and benefits of switching from HFO and <0.5% S residual fuel to alternative fuels

2. Background

2.1 Environmental and economic risks of HFO in the Arctic

HFO consists of the leftover residues from the oil refining process; for this reason, HFO is categorized as a "residual fuel." Although HFO powers fewer than half of the ships operating in the IMO Arctic, the ships that do operate on HFO tend to be larger and carry more fuel than ships that operate on cleaner distillate fuels. As such, HFO accounts for more than 75% of the fuel onboard ships operating in the Arctic (Comer, Olmer, & Mao, 2016).

Both the use of HFO by ships in the Arctic and its carriage as fuel and cargo pose considerable risks. Cold water temperatures prevent viscous HFO from dispersing or degrading naturally, thereby making HFO spills highly persistent in regions like the Arctic. Owing to its high density, HFO has negative buoyancy, causing it to sink rather than float on the surface. Sunken HFO can resurface during warmer seasons and wash ashore long after all surface spills have been cleaned up (Deere-Jones, 2016). Such unpredictable complexities and long-term effects of HFO spills exemplify the risks of using HFO in the Arctic region.

In addition to the risks of oil spills, burning HFO emits BC, a small, dark particle emitted as a result of incomplete combustion. When BC particles fall on light-colored snow and ice, they reduce the albedo of these surfaces. This causes more absorption of solar energy, more warming, and less ice (Comer and Olmer, 2016). The result is an accelerating feedback loop of warming and melting in the Arctic, an area already warming at more than twice the rate of the rest of the planet (Olmer et al., 2016). Studies have found that burning HFO tends to emit more BC emissions than other marine fuels (ICCT, 2016).

In addition to the environmental risks, cleaning up oil spills can be costly. Deere-Jones (2016) reported that cleaning up a single residual fuel oil spill routinely costs more than $100 million and can cost up to $360 million (2015 USD). For example, 1,200 tonnes of residual fuel oil were spilled when the Selendang Ayu bulk carrier ran aground near Unalaska Island, Alaska, in December 2004. Sadly, the wreck left six crewmembers dead. Cleanup was difficult because the site and oiled shorelines were accessible only by sea or by air and the effort was coordinated by the Kodiak, AK, Coast Guard station more than 1,000 kilometers away. Total cleanup costs reached $112 million (2005 USD), or roughly $93,000 (2005 USD) per tonne. Etkin (2000) conducted a more detailed analysis of the costs of cleaning up fuel oil spills. Etkin analyzed data from more than 300 oil spills and estimated the average cleanup cost for oil spills by fuel oil type, as shown in Table 1.

Table 1. Average marine oil spill cleanup costs by oil type. Source: Etkin (2000).

Oil type	Cost (1999 USD/tonne)
No. 2 fuel (diesel) (similar to marine distillate fuel)	2,308
No. 6 fuel (similar to HFO)	16,952

The present study uses data from Etkin (2000) to inform estimates of cleanup costs for marine fuel oil spills, as described in Section 3. As demonstrated by the Selendang Ayu disaster, cleanup costs for spills in remote locations can be more expensive than the average cleanup costs reported by Etkin. Although the Etkin study was published in 2000, we are not aware of more recent, comprehensive, and publicly available data on the relative costs of cleaning up different types of marine fuel oils. Thus, we base our estimates on the relative costs of cleaning up HFO and distillate fuels on Etkin's work (see Section 3).

2.2 Alternatives to HFO

The most common and widely available alternative to HFO is distillate fuels. Distillate fuels, such as marine diesel oil (MDO) and marine gas oil (MGO), are more refined and higher quality than HFO. Ships that burn HFO can use distillate fuel, and the fuel system modifications required for a ship to operate on MDO or MGO instead of HFO are minimal.[2] Indeed, ships routinely switch from HFO to MGO when entering European and North American waters that are designated as Sulfur Emission Control Areas (SECAs). Moreover, using distillate fuels instead of HFO reduces air pollutant emissions (see Tables 2-9 in U.S. EPA, 2009). An added advantage of distillate fuels relative to HFO is that spills of distillate fuel often require little or no cleanup, as they tend to evaporate or dissolve from the spill scene before responders reach the location (Etkin, 2000).

Liquefied natural gas (LNG) has emerged as an alternative to traditional petroleum-based fuels, but converting a petroleum-fueled ship to operate on LNG is expensive, and portside LNG fueling infrastructure is scarce. Thus, LNG-powered ships tend to be either LNG carrier vessels (which use their cargo as fuel) or newly built ships that are designed to operate on LNG. In 2015, only 7 of

2 Minimal changes include switching to fuel pumps with reduced plunger clearance, replacing fuel valves, altering the fuel injection timing to correspond to the altered calorific value of the fuel, using finer fuel filters, etc. These changes require minimal capital expenditure.

the 2086 ships operating in the IMO Arctic operated on LNG, according to the ICCT (Comer et al., 2017).

To a limited extent, biofuels (e.g., methanol) and fuel cells could potentially serve as an alternative to HFO in the Arctic. At present, methanol marine engines are rare, but methanol engines were ordered on a recently commissioned Stena RoPax ferry (Lloyd's Register, 2015). Hydrogen-powered fuel cells have limited use in tugboats and other small vessels but could be developed for larger cargo ships in the future. Other propulsion technologies, such as nuclear power, are available but are primarily used for naval vessels and icebreakers.

3. Methodology

This study analyzes the economic tradeoffs involved in the use of different types of marine fuel in the IMO Arctic, based on fuel consumption, fuel cost, and cleanup cost of HFO versus alternative fuels (distillate and LNG). Results are estimated for 2015 and projected to 2020 and 2025. The environmental tradeoffs of switching from HFO to alternative fuels are qualitatively discussed.

3.1 Fuel consumption and fuel carried

Fuel consumption and fuel carriage data for 2015 are taken from Comer et al. (2017). Comer and colleagues estimated fuel consumption and fuel carriage on the basis of ship activity from satellite Automatic Identification System (AIS) data from exactEarth and ship characteristics data from IHS for ships operating in the IMO Arctic region during the entire 2015 calendar year. Fuel consumption and fuel carriage projections for ships in the IMO Arctic in 2020 and 2025 were estimated using growth factors derived from Winther et al. (2014).

As a result of IMO's recent decision to implement a 0.5% global marine fuel S cap in 2020, consumption of residual fuel is expected to shift from traditional HFO (~2.6% S by weight[3]) to desulfurized or blended residual fuels that contain a mix of HFO and low-S distillate fuels meeting the 0.5% standard (referred to as <0.5% S residual fuel in this study). Comer et al. (2017) used the marine fuel demand assumptions in the IMO fuel availability study (Faber et al., 2016) to estimate the proportions of HFO and <0.5% S residual fuel consumed and carried onboard ships in 2020 and 2025. Accordingly, the present study assumes that demand for residual fuel in those years will be met primarily from <0.5% S residual fuel (88% of total residual fuel demand[4]) and the rest will be HFO (12% of total residual fuel demand), assuming that some ships will continue to operate on HFO and comply with the 0.5% S standard using scrubbers.

Fuel consumption and fuel carriage estimates for 2015 and projections to 2020 and 2025 are shown in Table 2. Total fuel consumption and carriage are expected to grow modestly in both 2020 and 2025 relative to 2015. However, the use and carriage of HFO are expected to decrease as a result of the implementation of the 0.5% global fuel S cap, although some HFO will continue to be used in conjunction with scrubbers, and demand for 0.5% S–compliant fuel will likely be met with desulfurized residual fuel and fuels blended with HFO. Indeed, nearly 60% of the fuel used and more than 75% of the fuel carried by ships in the IMO Arctic in 2020 and 2025 is expected to be HFO or <0.5% S residual fuel. However, if we take potential diversions of traffic from the Suez and Panama canals into account, as Comer et al. (2017) have done, the use and carriage of HFO and <0.5% S residual fuel are expected to increase more than 35% relative to the Business as Usual (BAU) growth scenario. The present study is based on projections of fuel use and carriage under BAU scenarios. Under all scenarios, both consumption and carriage of distillate are expected to increase, but only modestly. Consumption of LNG is expected to rise as a result of increased ship activity, but total LNG carriage will remain roughly the same.

3.2 Fuel price

The prices of marine fuels (HFO, <0.5% S residual, distillate, and LNG) in 2015 and 2020 (projected) are the same as those found in Faber et al. (2016). For 2025, the prices of HFO, <0.5% S residual fuel, and distillate fuel are projected by assuming that they track with the projected change in crude oil prices, as a close comparison of crude oil prices versus HFO and distillate prices over the years reveals a high correlation (Figure 2). The projected price of crude oil for the year 2025, $82.60/barrel, comes from the World Bank (2016). The price of LNG in 2025 was estimated from the projected change in natural gas prices for Europe and the United States as found in the 2016 World Bank Commodities Price Forecast.[5] All prices were converted to 2015 USD using the World Bank

3 MEPC 69/21, paragraph 5.29; MEPC.1/Circ.862; MEPC 70/18, section 5.

4 Total residual fuel demand for regions with Arctic territory (Europe, North America, and Russia), as estimated in Faber et al. (2016), is 99 Mt, of which 87 Mt (~88%) is <0.5% S residual fuel and the rest (~12%) is >0.5% S residual fuel (e.g., HFO).*

5 The price of natural gas in the United States and Europe is expected to increase 92% and 9.6%, respectively, from 2015 to 2025. We take the average of these values and assume that the price of LNG in the IMO Arctic will increase 51% from 2015 to 2025.

** Footnote corrected from an earlier version of the report.*

Table 2. Fuel consumption and carriage in the IMO Arctic.

	BAU growth scenario						With diversions through the Arctic from Panama and Suez canals	
	2015		2020		2025		2020	2025
	Tonnes	Percentage of total fuel used	Tonnes	Percentage of total fuel used	Tonnes	Percentage of total fuel used	Tonnes	Tonnes
Fuel used								
HFO	**249,043**	**58%**	**31,214**	**7%**	**32,152**	**7%**	**42,592** (+36%)*	**44,170** (+37%)
<0.5% S residual fuel	—	—	**228,901**	**51%**	**235,779**	**51%**	**312,335** (+36%)	**323,914** (+37%)
Distillate	182,730	42%	185,604	42%	185,810	42%	185,604	185,810
LNG	403	<0.1%	436	<0.1%	456	<0.1%	436	456
Total	*432,177*	*100%*	*446,154*	*100%*	*454,197*	*100%*	*540,967*	*554,350*
Fuel carried								
HFO	**834,655**	**76%**	**100,997**	**9%**	**101,821**	**9%**	**137,812** (+36%)	**139,881** (+37%)
<0.5% S residual fuel	—	—	**740,646**	**67%**	**746,690**	**67%**	**1,010,611** (+36%)	**1,025,805** (+37%)
Distillate	255,172	23%	255,860	23%	256,500	23%	255,860	256,500
LNG	4,152	<1%	4,160	<1%	4,157	<1%	4,160	4,157
Total	*1,093,979*	*100%*	*1,101,663*	*100%*	*1,109,168*	*100%*	*1,408,443*	*1,426,343*

*Values in parentheses are percent change from BAU scenario for the same year.

Manufacturers Unit Value (MUV) index[6] to adjust for projected inflation.

Because marine fuels have different energy densities, one must compare the price of the fuel per unit of energy. The energy density of residual fuels and distillates, reported in units of mega-joules per kilogram (MJ/kg), is roughly the same: about 40 MJ/kg (Lin, 2013). This study assumes that the energy density of <0.5% S residual fuel will also be around 40 MJ/kg. The energy density of LNG is approximately 50 MJ/kg (Alternative Fuels Data Center, 2014). This means that if one were to switch from a petroleum-based marine fuel (HFO, <0.5% S residual, or distillate) to LNG, one would need to bunker 20% less fuel by mass for the same amount of energy, although the volume of LNG needed would be higher than the energy-equivalent volume of residual or distillate fuels. Figure 3 and Figure 4 show the price of marine fuels in USD/tonne and USD/MJ, respectively.

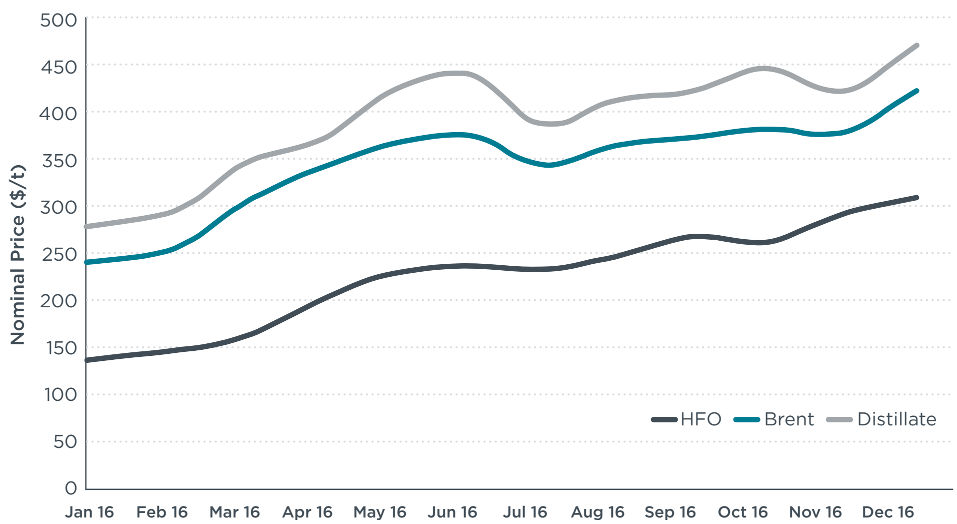

Figure 2. Prices of HFO, distillate, and crude oil from Ship & Bunker[7] historical fuel prices.

6 Available from Knoema at https://knoema.com/WBMFRUVI2014Nov/manufactures-unit-value-index-muv-world-bank-2014?tsId=1000000.

7 Ship & Bunker historical fuel prices available at http://shipandbunker.com/prices.

3.3 Cleanup costs

In addition to the ecological, social, and cultural costs of oil spills, there are economic costs. Etkin (2000) estimated the cost of cleaning up marine oil spills for a variety of fuel types, including No. 2 fuel (diesel) and No. 6 fuel (also called "Bunker C"). This report assumes that the cost of cleaning up HFO is similar to the cost of cleaning up No. 6 fuel and that the cost of cleaning up distillate is similar to the cost of cleaning up No. 2 fuel. Because <0.5% S residual fuel includes a larger percentage of lighter distillate fuel oil than does HFO, its cleanup costs are assumed to be 25% less than for HFO. Some of the distillate fuel fraction will evaporate off, which reduces the total amount of fuel in the water, in turn reducing cleanup costs. The actual cleanup costs of <0.5% S residual fuel are to be determined, as widespread use of this fuel will begin in 2020. Table 3 shows the estimated cleanup costs based on the World Bank (2016) MUV.

Table 3. Estimated cleanup costs of fuel oil spills.

Fuel type	Cost (2015 USD/tonne)
HFO	22,441
<0.5% S residual	16,831
Distillate (MGO)	3,055

3.4 Fuel costs

Fuel costs for ships operating in the IMO Arctic in 2015, 2020, and 2025 were estimated from the amount of fuel consumed (tonnes or MJ) in 2015 and projected BAU fuel consumption in 2020 and 2025, as reported in Section 3.1, and the price of fuel (USD/tonne or USD/MJ), as reported in Section 3.2, as follows:

$$FC_{i,y} = P_{j,y} \times Q_{j,y}$$

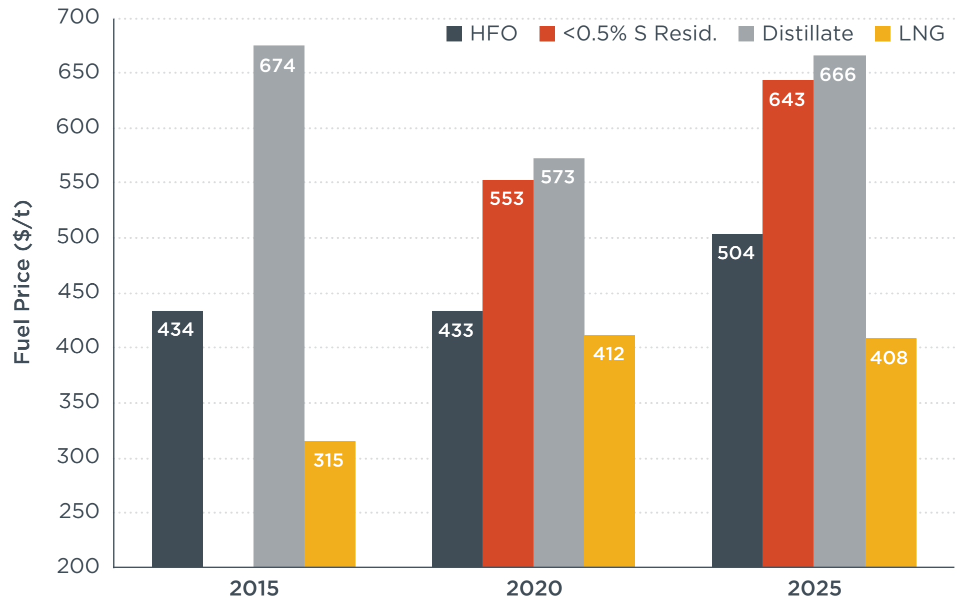

Figure 3. Price of marine fuels (2015 USD/tonne).

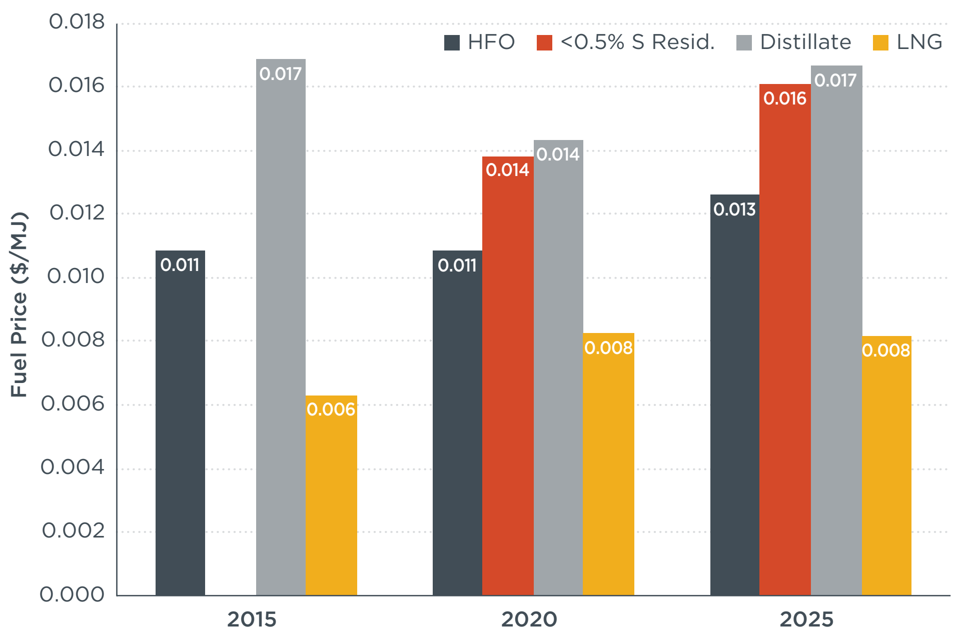

Figure 4. Price of marine fuels (2015 USD/MJ).

where

i = a given ship operating in the IMO Arctic
y = year
j = the fuel that ship i operates on (HFO, 0.5% S residual fuel, or LNG)

$FC_{i,y}$ = fuel cost for ship i in year y
$P_{j,y}$ = price of fuel j (USD/tonne or USD/MJ) in year y
$Q_{j,y}$ = quantity of fuel j consumed (tonnes or MJ) by ship i in year y

3.5 Costs of switching from HFO or <0.5% S residual fuel to alternative fuels

The costs of switching from HFO or <0.5% S residual fuel to alternative fuels are based on the quantity of fuel demanded in a given year, the relative difference in the energy content of the fuels that would replace HFO or <0.5% S residual fuel, and the difference in price between HFO or <0.5% S residual fuel and the alternative fuel. The cost of switching from HFO or <0.5% S residual fuel to alternative fuels was estimated as follows:

$$CS = Q_r \times (ED_r / ED_a) \times (P_a - P_r)$$

where

r = residual fuel (HFO or <0.5% S residual fuel)
a = alternative fuel (distillate or LNG)
CS = the cost to switch from fuel r to fuel a
Q_r = the quantity of fuel r demanded by the IMO Arctic fleet
ED_r = the energy density (MJ/kg) of fuel r
ED_a = the energy density (MJ/kg) of fuel a
P_a = the price of fuel a
P_r = the price of fuel r

Note that there are additional capital costs associated with continuing to use HFO and with switching to LNG that are not accounted for in this analysis. A ship operator wishing to continue to operate on HFO after 2020 will need to use a scrubber to comply with the sulfur regulations in MARPOL Annex VI Regulation 14. If, like the vast majority of vessels, the ship is not already outfitted with a scrubber, one will need to be installed. The price of a scrubber is approximately $6 million (Faber et al., 2016). A ship operator wishing to switch from petroleum-based fuels to LNG will need to retrofit the ship's fuel and propulsion systems at a cost of roughly $1.4 million per megawatt (MW) of installed engine power for a newly built ship (Faber et al., 2016); costs could be different for a retrofit. IMO (2016) estimated the cost of converting a 14 MW ferry from distillate to LNG at $32 million (~$2.2 million per MW). According to the IHS database and internal ICCT analysis, the average power of a ship in the IMO Arctic is around 5.5 MW. If one conservatively assumes that the cost of converting a ship to operate on LNG is $1.4 million per MW, this suggests an average cost of conversion near $8 million. However, the most powerful container vessel operating in the IMO Arctic has main engine power of nearly 70 MW, so the cost to convert to LNG could be very large, depending on the ship.

3.6 Break-even analysis

The cost of switching the fleet of vessels operating on HFO or <0.5% S residual fuel in the IMO Arctic to alternative fuels could be balanced by the avoided costs associated with cleaning up a residual oil spill. This report estimates the quantity of HFO or <0.5% S residual fuel that would need to spill from the fleet in a given year to make the costs of cleaning up the spill equivalent to the benefits (fuel cost savings) of continuing to operate on residual fuels. Any amount of residual oil spilled beyond the break-even point would result in a situation where the economic benefits of continuing to operate on residual fuels are outweighed by the economic costs of cleaning up a residual oil spill. The break-even analysis is conducted as follows:

$$BEQ = CS / (CC_r - CC_a)$$

where

r = residual fuel (HFO or <0.5% S residual fuel)
a = alternative fuel (distillate or LNG)
BEQ = break-even quantity: The amount of fuel r (tonnes) spilled beyond which the economic benefits of continuing to operate on fuel r are outweighed by the economic costs of cleaning up a spill of fuel r
CS = the cost to switch from fuel r to fuel a, as defined in Section 3.5
CC_r = cleanup costs (USD/tonne) for fuel r
CC_a = cleanup costs (USD/tonne) for fuel a

4. Results

4.1 Fuel costs

Total fuel costs for ships operating in the IMO Arctic are expected to increase from 2015 to 2020 and 2025 (Figure 5). This increase is driven by expected increases in fuel consumption (due to projected increases in Arctic shipping activity) and a high price of <0.5% S residual fuel in 2020 and 2025 relative to the price of HFO, which met all of the residual fuel demand in 2015.

4.2 Costs of switching to alternative fuels

The cost of switching from residual fuels to distillate or LNG is based on the relative price of marine fuels in 2015, 2020, and 2025 and the quantity of alternative fuel needed to replace the residual fuel. Table 4 shows the quantity of alternative fuel (distillate or LNG) that would be needed to replace HFO or <0.5% S residual fuel, based on the relative energy contents of the fuels, the difference in price (2015 USD per tonne) between the fuels, and the total change in fuel costs incurred in switching from residual fuels to distillate or LNG.

The additional economic costs or benefits of switching from residual fuels to alternative fuels can be estimated from these data. In 2015, it evidently would have been quite expensive for the Arctic fleet to switch from HFO to distillate fuels (~$60 million), based on the quantity of HFO that would need to be replaced with distillate. Given that the Arctic fleet spent approximately $230 million on fuel in 2015 (Figure 5), this would represent a 30% increase in total fuel expenditures for the fleet. Although switching from HFO to distillate in 2015 would have increased an individual ship's fuel costs by 55%, the cost to shift all ships in the fleet from HFO to distillate in 2015 would have increased fleetwide fuel costs by only 30% because more than half of the ships in the IMO Arctic would already be using distillate fuel.

A narrowing price gap between HFO and distillate means that an individual ship's fuel costs would increase 32% if it switched from HFO to distillate in 2020 or 2025. The cost to switch all ships in the Arctic fleet from HFO to distillate would be much less in 2020 and 2025 than in 2015, as HFO is expected to represent only 7% of the fuel used by ships in the IMO Arctic (down from 58% in 2015) as a result of the implementation of the 0.5% global fuel S standard in 2020. To switch all ships in the Arctic fleet from HFO to distillate fuel in 2020 or 2025 would cost the entire fleet roughly $4.3 million (2015 USD) in 2020 or $5.2 million in 2025, an increase in fleetwide fuel costs of less than 2%.

Similarly, switching all ships operating on <0.5% S residual fuel in the Arctic fleet to distillate in 2020 or 2025 would increase fleetwide fuel costs less than 2%: $4.5 million (2015 USD) in 2020 or $5.4 million in 2025. This would be

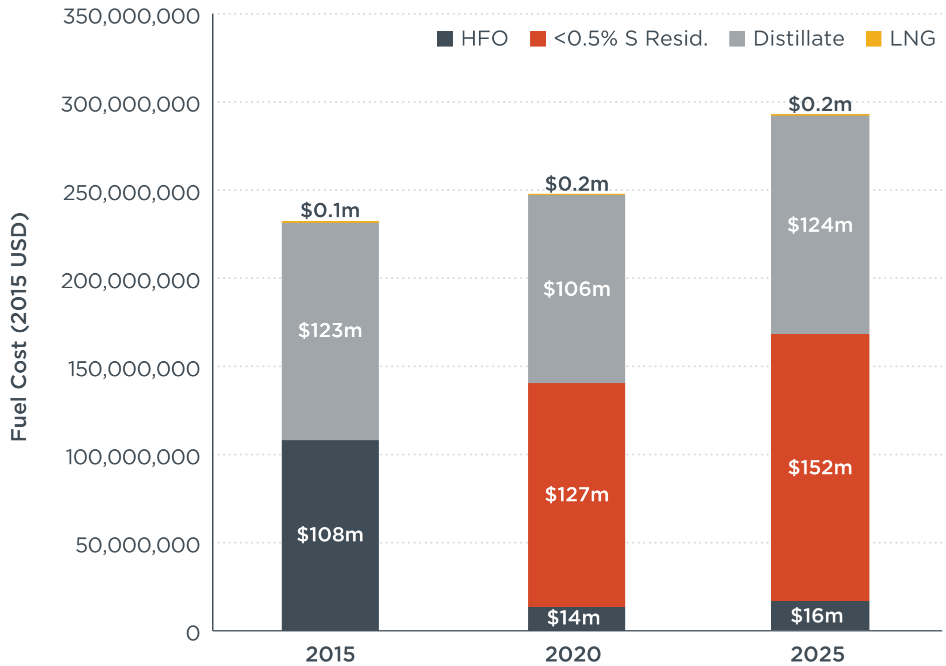

Figure 5. Fuel costs (2015 USD) of the entire IMO Arctic fleet.

Table 4. Costs (positive values) and benefits (negative values) of switching from residual fuels to distillate or LNG.

	2015	2020	2025
Alternative fuel needed (tonnes)			
HFO to distillate	249,043	31,214	32,152
HFO to LNG	199,235	24,971	25,721
<0.5% S residual to distillate	—	228,901	235,779
<0.5% S residual to LNG	—	183,121	188,623
Change in fuel price (2015 USD/tonne)			
HFO to distillate	240 (+55%)*	139 (+32%)	162 (+32%)
HFO to LNG	−119 (−27%)	−21 (−5%)	−96 (−19%)
<0.5% S residual to distillate	—	20 (+4%)	23 (+4%)
<0.5% S residual to LNG	—	−141 (−25%)	−235 (−37%)
Total change in fuel cost (2015 USD)			
HFO to distillate	$59,770,320	$4,338,746	$5,208,624
HFO to LNG	-$23,708,965	-$524,391	-$2,469,216
<0.5% S residual to distillate	—	$4,578,020	$5,422,917
<0.5% S residual to LNG	—	-$25,820,061	-$44,326,405

*Values in parentheses are percent change in fuel price (2015 USD per tonne) versus the price of HFO or <0.5% S residual fuel in that year.

the case even though <0.5% S residual fuel is expected to make up 51% of fuel demand for ships in the IMO Arctic. Hence, the cost to replace the roughly 230,000 tonnes of <0.5% S residual fuel that could be consumed in the IMO Arctic in 2020 or 2025 with distillate fuel may be less than $20 per tonne.

The price of LNG is expected to be less than that of HFO and <0.5% S residual fuel in 2020 and 2025; however, most ships in the IMO Arctic would need to be converted to operate on LNG at considerable expense. This would limit the potential use of LNG as an alternative fuel in the Arctic for existing ships in the near term, but some ships may undergo conversion in the medium term if the price of LNG remains low and ship owners find the payback period acceptable.

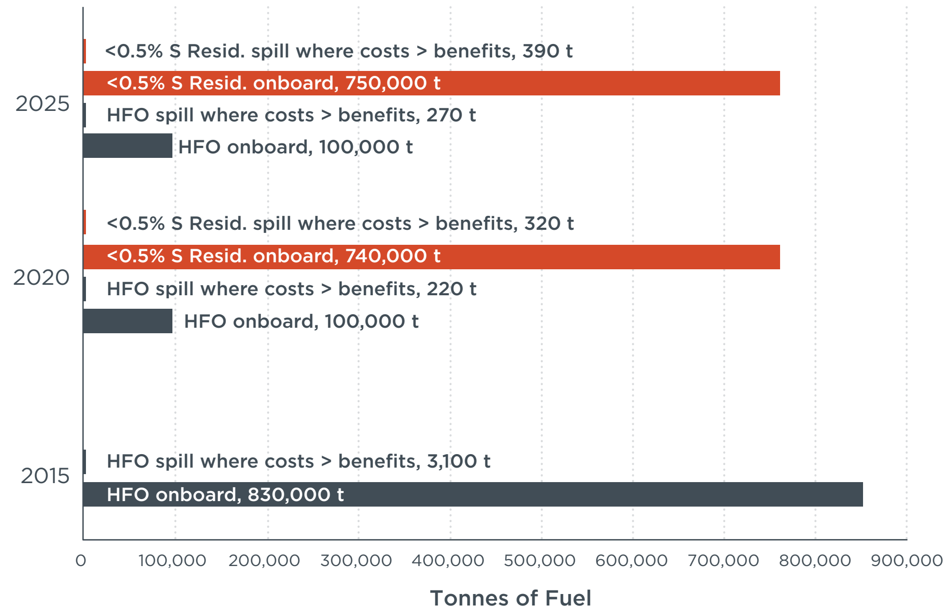

Figure 6. HFO and <0.5% S residual fuel onboard ships in the IMO Arctic compared to the size of a spill where the costs of cleaning up the spill exceed the economic benefit of operating on the fuel.

4.3 Break-even point

At a certain point, the cost of switching all ships operating on HFO or <0.5% S residual fuel in the Arctic fleet to alternative fuels would be outweighed by the avoided costs associated with cleaning up a residual oil spill. Given the costs of cleaning up oil spills (Table 3), a spill of even a small quantity of HFO or <0.5% S residual fuel could outweigh the fleetwide fuel cost savings of continuing to operate on these fuels. Operating on LNG is expected to remain cheaper on a USD/MJ basis from 2015 to 2025. Thus, if a ship were capable of operating on LNG, and LNG were available for bunkering, it would make sense to use LNG. However, ships would need to be retrofitted to operate on LNG, as previously discussed.

Operating on distillate, on the other hand, is expected to be more expensive (in USD/MJ) than operating on HFO or <0.5% S residual fuel. Thus, there is an economic incentive for ship operators to continue to use residual fuels rather than switch to distillates. The risk, however, is that the cost of cleaning up a residual oil spill (which would likely be paid by the ship's P&I club[8]) is estimated to be more than 7 times as expensive (in USD/tonne) as cleaning up a distillate fuel oil spill. This study finds that the additional costs of cleaning up even a very small quantity of HFO or <0.5% S residual fuel would outweigh the fuel cost savings of operating on these fuels (Figure 6). If, in 2020 or 2025, a ship in the IMO Arctic fleet were to spill 280 tonnes of HFO—an amount equivalent to less than 1% of the HFO used fleetwide or 0.25% of the HFO carried fleetwide in those years, as estimated in Table 2—it would be less expensive for the entire fleet to operate on distillate fuel rather than continuing to operate on HFO when taking the cleanup cost of this one spill into account. Even less <0.5% S residual fuel (by percentage) would need to be spilled for the cleanup costs to exceed the fuel cost savings of continuing to operate on residual fuel.

For some context, Det Norske Veritas (DNV; 2017) estimated that roughly 100 tonnes of oil (bunker + cargo) per year would be accidentally spilled from the ~1350 ships they found operating in the IMO Arctic in 2012. Comer et al. (2017) estimate that ~2,100 ships operated in the IMO Arctic in 2015, about 55% more ships than DNV's estimate. Accordingly, one could expect 155 tonnes of oil to be spilled in a given year. If 100 tonnes of that is HFO, every 2 or 3 years one could expect the cost of cleaning up an HFO spill to exceed the fleetwide cost savings of using HFO. Furthermore, approximately 75% of ships that use HFO have bunker tanks capable of carrying at least 280 tonnes of fuel. This means that a single ship could spill enough HFO where the potential cost savings of operating on residual fuel are outweighed by the cleanup costs.

8 A P&I club is a mutual insurance association that provides risk pooling, information, and representation for its members.

5. Policy Alternatives

The continued use of HFO, along with the expected rise in marine traffic, suggests that the probability of a harmful oil spill in the Arctic will continue to increase. At the conclusion of the 70th session of the IMO Marine Environmental Protection Committee (MEPC 70), work to assess the risks of HFO in the Arctic was considered, and there may be opportunities to develop policy alternatives to address such a risk. The following provides a sample of policy alternatives and their implications for the Arctic, given the results of this study.

5.1 Business as usual: Use of HFO in the Arctic remains regulated

Left unregulated, HFO will likely continue to be used in the Arctic. Despite implementation of the 0.5% global fuel S cap in 2020, HFO will continue to be used by ships whose owners and operators choose to comply with the regulation by using scrubbers. Additionally, 0.5% S–compliant fuels will likely be desulfurized residual fuel or residual fuel blends that may be just as harmful to the environment as HFO.

5.2 Alternative 1: Designate the Arctic region as a SECA (<0.1% S)

Designating the Arctic region as a Sulfur Emission Control Area (SECA) would be a positive step toward eliminating the use of HFO in the Arctic. The ship owner or operator desiring to comply with an Arctic SECA would primarily be choosing from among scrubbers, distillate fuel, and LNG. Given that the projected price of LNG is expected to continue to be cheaper than distillate, some ship owners may opt for LNG propulsion technologies. However, an SECA would not prohibit the use of HFO in the Arctic, as ships could comply with fuel S standards through the use of scrubbers, which would enable the ship to continue to operate on (and carry) high-S HFO. Thus, an SECA would not prohibit the carriage of HFO and therefore would not reduce the ecological dangers associated with HFO spills in the Arctic.

5.3 Alternative 2: Prohibit the use of HFO (no limitation on carriage)

Prohibiting the use of HFO in the Arctic would reduce climate-warming BC emissions in the Arctic. However, such a scenario allows large vessels to continue transporting HFO through the Arctic, and therefore the risk of an HFO spill would persist.

5.4 Alternative 3: Prohibit the use and carriage of HFO, desulfurized residual fuel, or residual fuel blends

Prohibiting the use and carriage of HFO in the Arctic would greatly reduce the risks of environmental damage from oil spills and would also reduce emissions of climate pollutants, including BC. One could envision a prohibition of the use of HFO, desulfurized residual fuel, or residual fuel blends to promote a shift to distillates, LNG, or other alternative fuels. Prohibiting the use of HFO combined with prohibiting the carriage of HFO as fuel or ballast, as is the case in the Antarctic, would offer the greatest protection against HFO spills in the Arctic. However, exceptions could be made for the carriage of HFO cargoes for community resupply.

5.5 Alternative 4: Prohibit the use of any petroleum-based fuel oil in the Arctic

A complete prohibition on the use of petroleum-based fuel oil in the Arctic would immensely reduce air emissions, including BC, and would mitigate the risks of oil spills in the Arctic. Essentially, this would mean that ships would need to operate on LNG, a biofuel, or electricity (fuel cells). This scenario provides the greatest protection to the Arctic environment from HFO and distillate spills, but nearly all of the vessels that currently operate in the IMO Arctic would not be able to comply with such a requirement. This policy alternative is unlikely to garner support from the maritime shipping industry and IMO member states for now.

6. Conclusions

The use and carriage of HFO in the Arctic are likely to continue, despite policies such as the 0.5% global fuel S cap that aim to improve the quality of marine fuels. In fact, compliance with the 0.5% global fuel S cap is expected to be met primarily through the use of <0.5% S residual fuel. Nearly 60% of the fuel used and more than 75% of the fuel carried by ships in the IMO Arctic in 2020 and 2025 is expected to be HFO or <0.5% S residual fuel. Thus, the Arctic is expected to continue to be at risk from residual fuel oil spills and elevated BC emissions.

Switching from HFO to distillate would increase an individual ship's fuel costs by 32% to 55%, depending on the year. Switching all of the Arctic ships that operate on HFO to distillate in 2015 would have increased fleetwide fuel costs by only 30% because more than half of the ships in the IMO Arctic already operate on distillate fuel. In 2020, the costs of switching the entire IMO Arctic fleet are likely to be substantially lower than today because the implementation of the 0.5% global fuel S standard in 2020 is expected to greatly reduce the amount of HFO used by ships in the Arctic.

We conclude that a switch from HFO to distillate fuel in 2020 or 2025 would cost the Arctic fleet roughly $4.3 million to $5.2 million (2015 USD), an increase in fleetwide fuel costs of less than 2%. With the implementation of the 0.5% fuel S standard in 2020, most ships that currently operate on HFO are expected to use desulfurized residual fuel or residual fuel blends that comply with the standard instead of switching to more expensive distillate fuel. This study projects a small price difference between <0.5% S fuel and distillate, however, meaning that switching all of the ships in the IMO Arctic fleet that use <0.5% S residual fuel to distillate in 2020 or 2025 would increase fleetwide fuel costs by $4.5 million to $5.4 million. This suggests a total cost of approximately $9 million to $11 million[9] (2015 USD) to switch all of the ships in the Arctic fleet that use HFO or <0.5% S residual fuel to operate on distillate in 2020 and beyond.

Although continuing to operate on HFO or residual fuel blends in the Arctic offers some economic benefits relative to operating on distillate fuels, the cleanup costs (per tonne) of residual fuel oil spills are more than 7 times those of a distillate spill, and even a relatively small spill of HFO or <0.5% S residual fuel—less than 1% of the amount of these fuels expected to be carried on ships in the Arctic in 2020 or 2025—would require cleanup expenditures that would outweigh the annual cost savings of continuing to operate on these fuels. If the other ecological and societal benefits of switching from HFO or residual fuel blends to distillate fuels are also taken into account (see, e.g., Deere-Jones, 2016), the argument for abandoning residual fuels is even stronger.

9 The approximate sum of switching all of the Arctic ships that operate on either HFO or <0.5% S residual fuel to distillate fuel in 2020 or 2025.

With respect to LNG, the study projects the price of LNG to be less than both HFO and <0.5% S residual fuel in 2020 and 2025; however, most of the fleet would need to be converted to operate on LNG, at considerable short-term expense. However, it is not out of the question for ships to convert to operate on LNG in the medium term if the price of LNG remains low and ship owners find the payback period acceptable.

Of the potential policy alternatives laid out above, prohibiting the use of any petroleum-based fuel oil in the Arctic (Alternative 4) provides the greatest long-term protection of the Arctic environment from the risks of spills and BC emissions from HFO and residual fuel blends. However, transitioning the Arctic fleet to operate on LNG, biofuels, or electricity (fuel cells) would take time, owing to the long operating lives of ships and the need for substantial investment in alterative fuel technologies and infrastructure. Nonetheless, LNG may be an attractive marine fuel for the Arctic if the price of LNG continues to be much less than that of distillate and residual fuel blends (thereby reducing the payback period of converting a ship to operate on LNG) and as LNG bunkering infrastructure becomes increasingly available in the region.

In the meantime, prohibiting the use and carriage of HFO, desulfurized residual fuel, or residual fuel blends (Alternative 3) offers a short-term solution that immediately reduces the risks of HFO to the marine environment. Implementing this alternative in 2020 or 2025 would be expected to increase IMO Arctic fleetwide fuel costs by $9 million to $11 million (2015 USD) but would eliminate the potential costs of cleaning up a spill of HFO or residual fuel blends—costs that have exceeded $100 million per incident in recent decades. Again, when one considers the additional ecological and social costs of residual fuel spills, the case for abandoning HFO, desulfurized residual fuel, and residual fuel blends is even stronger. Thus, while one may pursue a petroleum fuel–free Arctic as a long-term strategy, seeking a ban on the use and carriage of HFO, desulfurized residual fuel, or residual fuel blends could be done in parallel and could be accomplished in the near term.

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